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Lunar Habitat Optimization Using Genetic Algorithms

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LIST OF ACRONYMS

ANSYS	computer program
EVOH	ethylene-vinyl alcohol copolymer
FEA	finite element analysis
GA	genetic algorithm
GCR	galactic cosmic ray
MATLAB	computer program
PEEK	polyetheretherketone
SPE	solar particle event

NOMENCLATURE

A	surface area of the habitat
A_{Sun}	area of the habitat being radiated on by the Sun
a	absorptivity
c	constant used to calculate meteoroid mass
\dot{E}_{in}	energy into the system from outside sources
\dot{E}_{out}	energy loss from the system
\dot{E}_g	thermal energy generation
\dot{E}_{st}	rate of energy stored within the system
e	emissivity
F	number of particles/m ² /yr of mass, m , or greater
K	material constant
m	mass
m_p	mass of the projectile
P	depth of penetration (cm)
P_{NI}	probability of no impact
Q_{Cond}	conduction heat transfer rate
Q_{Rad}	radiation heat transfer rate
Q_{radHab}	effective radiation from habitat
Q_{radSun}	radiation heat transfer rate from the Sun
Q_{TOT}	tota heat transfer rate

NOMENCLATURE (Continued)

q_{Sun} incident heat flux from the Sun

R_{EQ} equivalent thermal resistance

T_i initial temperature

T_s surface temperature

t time (years)

V_p velocity of the projectile

β angle of impact

ε percent elongation

ρ_p density of the projectile

ρ_T target density

σ Stefan-Boltzmann constant

TECHNICAL PUBLICATION

LUNAR HABITAT OPTIMIZATION USING GENETIC ALGORITHMS

1. INTRODUCTION

The Nation's Vision for Space Exploration calls for a human return to the Moon by 2020 and a later potential human mission to Mars. These future missions are expected to involve much more impressive activities than those of the Apollo program. Some missions may last several months, and others may last up to 600 days.¹ These long-duration surface missions will require large outposts to accommodate living quarters (habitats) as well as indoor laboratory facilities. Transporting the materials required to build the necessary habitats will be costly and dangerous.² The greatest impediment to extended human presence on the Moon or Mars is the threat posed by the harsh environments found on their planetary surfaces and on the journey there. The lunar environment is much different than the terrestrial environment; many of the load conditions on the Moon are much more severe.²

Crew habitats require thermal insulation, structural support, impact resistance, and radiation protection. The temperature of the habitat and electronics contained within must be controlled.³ Temperatures on the Moon can range from 114 °C at lunar noon to –183 °C during lunar night.⁴ The Moon is essentially without an atmosphere and Mars' atmosphere is minimal; therefore, protection against meteoroids is also necessary. “For astronauts in a pressurized building that is suddenly pierced by a small meteorite, the chances of survival are problematic.”⁵ Ultraviolet and ionizing radiation penetrates to the lunar surface without any attenuation due to the vacuum environment of space and the lack of any lunar atmosphere.³ Cosmic radiation and solar particle events pose a risk to the crew on the surface of either the Moon or Mars.

To explore the solar system, a permanent base on the Moon is necessary, and “any large-scale permanent colonization of the Moon demands the use of locally available lunar materials, simply because the mass of materials needed in construction would be too great and too expensive to import from Earth.”² Through the use of in situ resources and terrestrial materials a habitat can be designed to protect against the hazards on the surface of the Moon and Mars.

The materials chosen for the habitat walls play a direct role in protection against each of the mentioned hazards. Multifunctional materials; e.g., radiation shielding that also has good thermal insulation properties, are an excellent way to provide protection since materials can be selected that meet not only the structural requirements but also afford good radiation and thermal protection as well.

Choosing the best materials, their configuration, and the amount required is extremely difficult due to the immense size of the design space. For example, a three-layer habitat wall created from 20 possible materials, all with varying thicknesses, would have the following number of possible solutions:

$$(\text{number of layers}) * (\text{possible material types})^{(\text{possible thicknesses})} = 72^\infty . \quad (1)$$

Clearly, some sort of optimization method would be extremely beneficial.

2. OPTIMIZATION

There are several optimization techniques, each having a number of advantages and disadvantages, that could apply. Standard optimization techniques are not suitable for problems with the large search space that will be encountered when designing a surface habitat. Standard (direct) optimization techniques (also referred to as “hill-climbing” techniques) seek local optima by moving towards the direction of the local gradient, and indirect techniques search for local extrema by solving a set of (typically nonlinear) equations that result from setting the gradient of the objective function equal to zero. Unfortunately, both methods only seek local optima.⁶

A genetic algorithm (GA) is a search algorithm based on the principles of evolution and natural genetics. A pseudocode example of a GA is shown in figure 1. GAs can be implemented as a population of binary strings or as a string of real-valued numbers, each string representing a solution to the problem. Genetic operators—crossover and mutation—are used to create the succeeding generation from the members (strings) of the current population. The algorithm is repeated until a stop criterion is reached; e.g., a certain number of generations are processed.⁷ Each individual is assigned a fitness based on how well it satisfies the objective function, which is calculated through engineering analysis. The probability of a design being propagated to the next generation as well as the frequency of occurrence of the design in the next generation is directly proportional to the fitness of the individual.⁶

```
Procedure GA(
    t = 0;
    Initialize P(t);
    Evaluate P(t);
    While (Not Done)
    {
        Parents(t) = Select_Parents(P(t));
        Offspring(t) = Procreate(Parents(t));
        Evaluate(Offspring(t));
        P(t+1)=
        Select_Survivors(P(t),Offspring(t));
        t = t + 1;
    }
}
```

Figure 1. Pseudocode version of a GA.

The use of GAs can greatly enhance the selection of materials that have more than one purpose, such as radiation, thermal, and impact protection, and multifunctional materials can save a considerable amount of mass when compared to standard design techniques. Combining the multifunctional materials with in situ resource utilization will allow a surface habitat to be designed with a minimal amount of up-mass.

3. BACKGROUND

3.1 Objective

The objective of this work was to develop a cross-disciplinary surface habitat optimization and analysis tool that can determine a near-optimal combination of materials for the walls of a surface habitat. The tool optimizes the habitat materials for minimum up-mass including the analysis of thermal losses and gains, structural integrity, meteoroid impact, and radiation shielding. A pictorial of the various objectives is shown in figure 2.



Figure 2. Multiobjective parameters for the lunar habitat design tool.

3.2 Thermal

The thermal stability of a lunar habitat is of extreme importance to the survival of the crew and continued viability of the habitat. A lunar habitat experiences drastic thermal cycling loads during a lunar day. Temperature extremes can vary 200 K on the surface of the Moon; therefore, it is necessary to design a structure that can sustain such dramatic thermal cycling loads. A “shirt-sleeve” environment is the ideal and preferred environment for astronauts. It is common knowledge that active heating and cooling is required for lunar habitats, and a reduction of such a need will reduce the up-mass of the required equipment. Therefore, thermal losses are calculated to determine the suitability of a given design.

3.3 Structural

Structural integrity of the lunar habitat is necessary to ensure that the habitat does not fail from overload conditions. A lunar habitat must be able to withstand many different structural loads including residual loads from the habitat itself, the pressure differential of the shirt-sleeve environment and the vacuum of space, impacts from meteoroids, and loads during construction phases. All of these loads are to be considered when evaluating the structural integrity of the lunar habitat. A safety factor of 1.1 was used to analyze a fully loaded habitat.

3.4 Meteoroid Impact

A meteoroid is a “naturally occurring solid body, traveling through space, which is too small to be called an asteroid or a comet.”⁸ It is estimated that meteoroids of $\approx 1\text{-mg}$ mass size strike lunar structures

yearly. Velocities of meteoroids at the Moon range from 13 to 18 km/s. Meteoroids of $\approx 10^{-6}$ g can generate craters of 500 μm in metals. Impacts of larger meteoroids are more rare; however, they pose a much more significant threat to the habitat. A meteoroid with a mass of ≈ 1 g can produce a centimeter-sized crater in metallic materials.⁸

3.5 Radiation

The radiation environment encountered in interplanetary space consists primarily of energetic ions and the galactic cosmic rays (GCRs). Further sources of radiation are solar particle events (SPEs) due to solar flare cycles. SPEs are infrequent events that occur with large coronal mass ejections, and result in a large amount of particles, mostly protons, moving through the solar system.⁹

GCRs originate outside our solar system, are regulated by the solar wind, and contain high-charge ions as well as alpha particles and protons. The heavy ions make up a small portion of the total particle fluence (particles per area during a given time); however, they are responsible for approximately half of the long-term dose equivalent.⁹

For long-term stays, the crew should have at least 400 g/cm² of regolith covering for adequate radiation protection, which does not account for solar flare events. However, 100–200 g/cm² of regolith intensifies the dosage due to secondary radiation.¹⁰ At least 2.5 m of regolith covering would be required to keep the annual dose of radiation at 5 rem.¹¹ The limit for astronauts in low Earth orbit is 25 rem, and the occupational limit for an adult is 5 rem/yr.

The addition of other materials could decrease the amount of regolith cover required for radiation protection. Hydrogen and materials that contain a large amount of hydrogen, such as polyethelyene and other polymers, have been shown to be good radiation shielding materials.⁹ A combination of lunar regolith and other materials would provide a good barrier to radiation.

3.6 Materials Database

The materials database contains all the necessary material properties for each of the analysis modules. Currently there are 24 materials in the database, including aluminum, polyethylene, Mylar®, regolith cement, polyetheretherketone (PEEK), stainless steel, Kevlar® and glass composites, rubber, and ethylene-vinyl alcohol copolymer (EVOH). Other materials can easily be added to the database; the name and properties are all that are required.

4. COMPUTER CODE DEVELOPMENT

The computer code was written primarily in MATLAB. Each analysis module was written as a separate subroutine. The optimization code is a GA written by the authors at NASA Marshall Space Flight Center.

4.1 Thermal

4.1.1 Steady State Numerical Thermal Model

A significant amount of research has been done to develop an analytical model of the multilayer insulation heat leak of the lunar habitat under consideration. Analysis of the habitat begins by the application of the first law of thermodynamics to the control volume.

This is a passive system, meaning that no additional heat comes in or is taken away by an active thermal control system. A depiction of this system is shown in figure 3, and the corresponding energy balance equation is

$$\dot{E}_{in} + \dot{E}_g + \dot{E}_{out} = \dot{E}_{st} , \quad (2)$$

where

\dot{E}_{in} is the energy into the system from outside sources

\dot{E}_{out} is the energy loss from the system

\dot{E}_g is the thermal energy generation

\dot{E}_{st} is the rate of energy stored within the system.

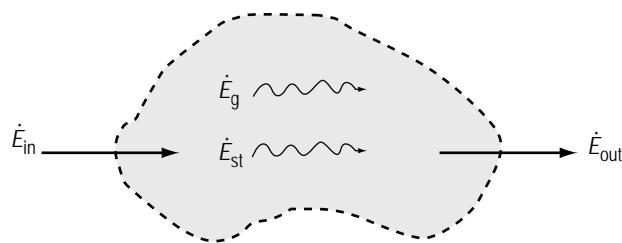


Figure 3. Theoretical control volume of the system.

The core problem of cooling and/or heating lunar habitats is the thermal radiation due to solar heating by direct and indirect means; i.e., directly from the Sun and indirectly from lunar reflection. The effective radiation heat flux equation from the Sun (or net energy absorbed from the Sun) is

$$Q_{\text{radSun}} = a \cdot A_{\text{Sun}} \cdot q_{\text{Sun}} , \quad (3)$$

where

a is absorptivity

A_{Sun} is the area of the habitat being radiated on by the Sun

q_{Sun} is the incident heat flux from the Sun.

The effective radiation from the habitat takes the form of

$$Q_{\text{radHab}} = e \cdot \sigma \cdot A \cdot T_S^4 , \quad (4)$$

where

e is the emissivity

σ is the Stefan-Boltzmann constant

A is the surface area of the habitat

T_S is the surface temperature.

Calculation of the surface temperature of the habitat requires the determination of the roots of a fourth degree polynomial. Equating the conduction and radiation heat transfer rates and the polynomial is shown in equation (8).

$$\begin{aligned} Q_{\text{Cond}} &= Q_{\text{Rad}} \\ \frac{(T_S - T_i)}{R_{\text{EQ}}} &= Q_{\text{TOT}} - e\sigma A T_S^4 \\ (Q_{\text{TOT}}) R_{\text{EQ}} - e\sigma A T_S^4 R_{\text{EQ}} - T_S + T_i &= 0 \\ Q = \left[\begin{matrix} R_{\text{EQ}} e\sigma A T_S^4 & 0 & 0 & -T_S & (Q_{\text{TOT}}) R_{\text{EQ}} + T_i \end{matrix} \right]. \end{aligned} \quad (5)$$

4.1.2 Finite Element Analysis Thermal Model

A finite element analysis (FEA) model of the thermal behavior of the lunar habitat was created in ANSYS, and an example result is shown in figure 4.

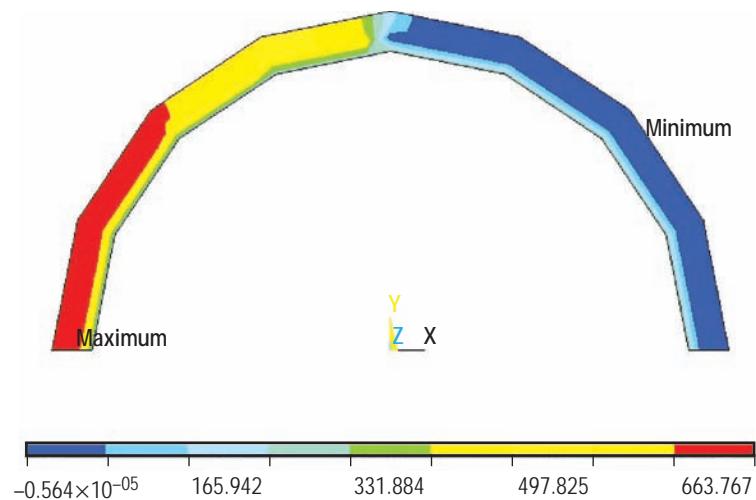


Figure 4. Example FEA thermal model.

4.2 Structural

A structural model was created and written in ANSYS. This structural model includes all loading conditions, including pressure differential and material weight in a 1/6-g environment. An example ANSYS plot is shown in figure 5.

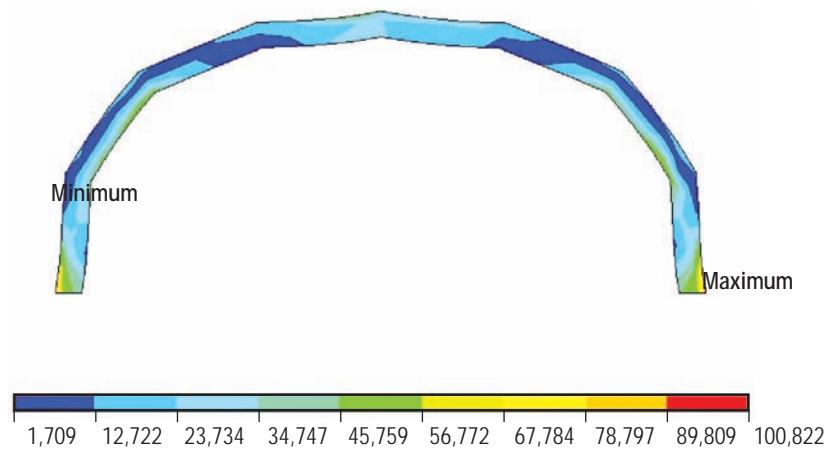


Figure 5. Example structural FEA model.

4.3 Meteoroid Impact

The meteoroid impact analysis was developed around the Fish-Summers single-plate penetration equation:¹²

$$P = Km_p^{0.352} \rho_p^{0.167} (V_p \cos \beta)^{0.875}, \quad (6)$$

where

P = depth of penetration (cm)

K = material constant

m_p = mass of the projectile

ρ_p = density of the projectile

V_p = velocity of the projectile

β = angle of impact.

The projectile density and velocity were assumed to be 0.5 g/cm³ and 20 km/s, respectively. The velocity is conservative, and the density is considered an estimate. The zero-degree angle of impact used was considered a conservative assumption.

The material constant can be approximated for each material with the following equation:¹³

$$K = \frac{0.816}{\varepsilon^{1/18} \sqrt{\rho_T}}, \quad (7)$$

where ε = percent elongation and ρ_T = target density.

The projectile mass was determined to be 0.22 g by iterating between equations (8) and (9) (Robinson, J.H.: Private Communication, April 7, 2005).¹⁴

$$F = c_0 \{(c_1 m^{0.306} + c_2)^{-4.38} + c_3(m + c_4 m^2 + c_5 m^4)^{-0.36} + c_6(m + c_7 m^2)^{-0.85}\}, \quad (8)$$

where

F = number of particles/m²/yr of mass, m , or greater

$c_0 = 3.156 \times 10^7$

$c_1 = 2.2 \times 10^3$

$c_2 = 15$

$c_3 = 1.3 \times 10^{-9}$

$c_4 = 10^{11}$

$c_5 = 10^{27}$

$c_6 = 1.3 \times 10^{-16}$

$c_7 = 10^6$.

$$P_{NI} = e^{-F*A*t}, \quad (9)$$

where

P_{NI} = probability of no impact

F = number of particles/m²/yr of mass, m , or greater

A = area (m²)

t = time (years).

To be conservative, the mass was calculated assuming a 32-m outer radius, 15-yr time span, and 95 percent probability of no impact.

Only the outside layer of the habitat wall was analyzed by the impact code because averaging all of the material constants (K) for each layer of the multilayered wall would have resulted in a less accurate penetration depth. Furthermore, this forces a tough outer layer to protect the habitat, which is the most realistic assumption.

4.4 Radiation

The radiation analysis is considered to be a rule-of-thumb, level-zero analysis. The thickness of each layer is converted into a corresponding thickness of aluminum and then the dose equivalent is calculated in the middle of the habitat.

The 1989 Solar Maximum radiation environment is used in this analysis because it is assumed to be a near-worst-case SPE. The radiation model only accounts for protons, but a 5 rem dose is added to account for any secondary neutrons created from the primary proton bombardment.

4.5 Materials Database

The materials database is contained as a matrix in a separate file accessed by the code. It contains all the necessary material properties to run each of the analysis modules. Also, a name matrix is contained in the same file, and it contains character strings of the names of each material type. This is used to generate output files and when creating the analysis plots.

4.6 Optimization

A GA was written specifically for the lunar habitat wall optimization problem. This GA uses a combination of crossover, mutation, and attrition to search the design region for a lunar habitat optimization problem.

GAs require few control parameters, and assuming the computational time and resources are not constrained, settings for these control parameters become less of an issue. However, if high-performance GAs that are able to find excellent solutions quickly are desired, then it is important to discover a set of optimal control parameter settings. In the GA literature, there are basically two approaches used in the discovery of high-performance control parameters: (1) An online approach (adaptation)¹⁵⁻¹⁸

and (2) an offline approach (discovery of robust control parameters).^{19,20} Online adaptive approaches seek to evolve appropriate control parameter settings for the GA during the evolutionary process. Control parameter settings that may work well one stage (beginning, middle, or later stages) of genetic search may not work well during the other stages. The online adaptive approaches are therefore developed to discover the most appropriate parameter settings to apply at the appropriate time during genetic search.

In the offline approach, the objective is to find a set of control parameter values that work well for a set of related applications. Shaffer, et al. and Grefenstette have developed a meta-GA for evolving robust control parameters for a simple GA.^{19,20} These parameters have been used as a guide for control parameter setting by GA researchers for solving a wide range of problems.⁶ In this Technical Publication (TP), a meta-GA is used to evolve a set of control parameter settings for population size, mutation rate, and mutation amount (perturbation amount or sigma). Each member of the meta-GA was evaluated five times to determine a reasonable fitness value for each member of the population.

4.7 Meta-Genetic Algorithm Results

The meta-GA focused on searching for three optimal GA parameters: (1) Population size, (2) mutation rate, and (3) mutation amount. The plots of these GA parameters are shown in figure 6. The optimal GA values determined follow:

- Population size = 150.
- Mutation rate = 0.332.
- Mutation amount = 0.6128.

The allowable ranges for the GA design parameters were set at 4–200 for population size and 0–1 for both mutation rate and mutation amount. A plot of the objective function versus generation for an example run using the optimal GA parameters is shown in figure 7.

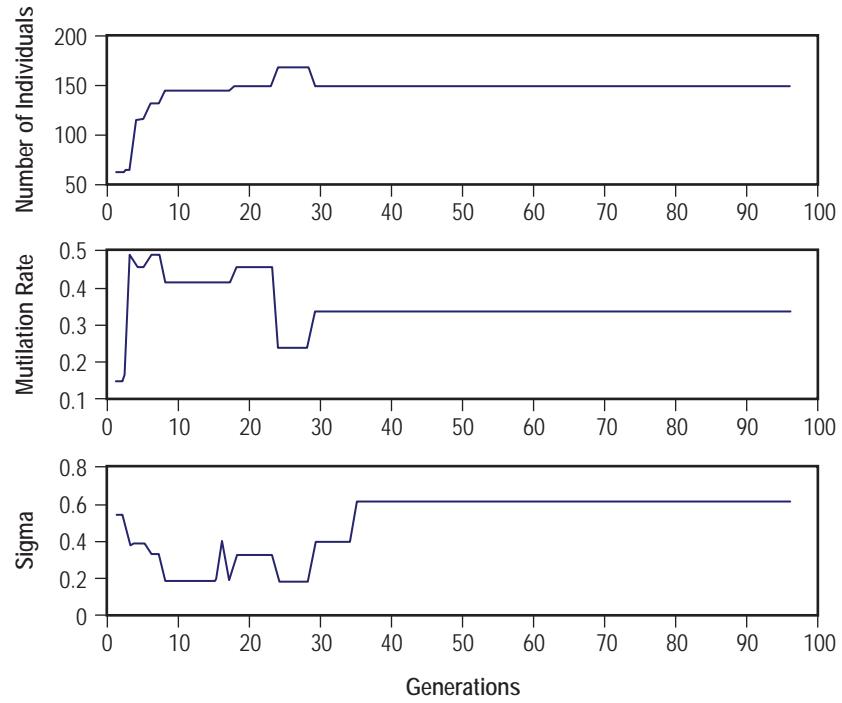


Figure 6. GA control parameter plots.

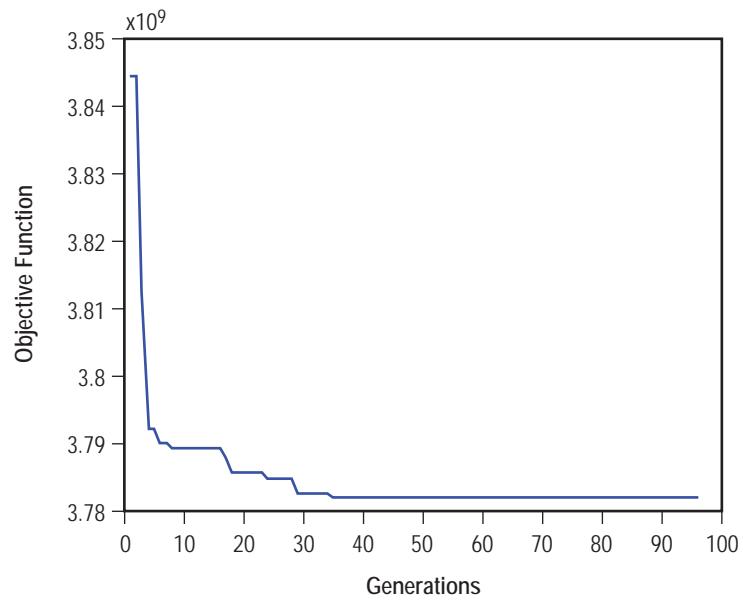


Figure 7. Meta-GA objective function plot.

5. OBJECTIVE FUNCTION FORMULATION

The habitat optimization tool described in this TP attempts to optimally combine several aspects pertinent to a superior lunar habitat design, as follows:

- Minimize thermal losses.
- Maintain structural integrity.
- Provide meteoroid and radiation protection.

Each of the mentioned parameters is independently calculated based on the material and geometric framework of the candidate habitat design. The difficulty lies in the weightings of the individual objectives in question. Two things to consider are: (1) Should they all be weighted equally, and (2) how is equality measured? These questions must be addressed in order to fully optimize a realistic lunar habitat design.

The weightings of the objective functions are simply a subjective measure of the designer's ordered priority. It may be the choice of the designer to emphasize the minimization of the active thermal control required to maintain the shirt-sleeve environment for the astronauts, or the designer may wish to emphasize meteoroid and radiation protection. Regardless of the designers choice, it is necessary to scale the objectives such that the weightings are initially equal. Recalling that the various objectives are measured in heat loss, deflection, penetration depth, and radiation dose. To equally weight these parameters, a series of 60 analyses were performed for this study. The objective weightings were changed sequentially to equalize the differing objective parameters. The final values are listed in table 1.

Table 1. Final equally scaled constraint factors.

Parameter	Factor
Up-mass	1
Heat loss	11.68
Deflection	872,227.76
Penetration depth	95,233.43
Radiation dose	51,064.29

The values in table 1 are simply an equal weighting representation of the individual objectives. At this point, the designer has the option of emphasizing one objective over another. Examples of designer-weighted objectives are given in section 6.

6. RESULTS AND DISCUSSION

The GA parameters, as chosen by the meta-GA, were applied to a single run of the lunar habitat design tool. This final run was compared to the following user-selected GA parameters:

- Population size = 40.
- Mutation rate = 0.20.
- Mutation amount = 0.20.

In order to provide an equal starting point, the intuitive parameter run utilized the best 40 individuals from the randomly generated initial population of the optimized parameter run. Figure 8 clearly demonstrates that the optimal GA parameters return a better solution with a much quicker convergence.

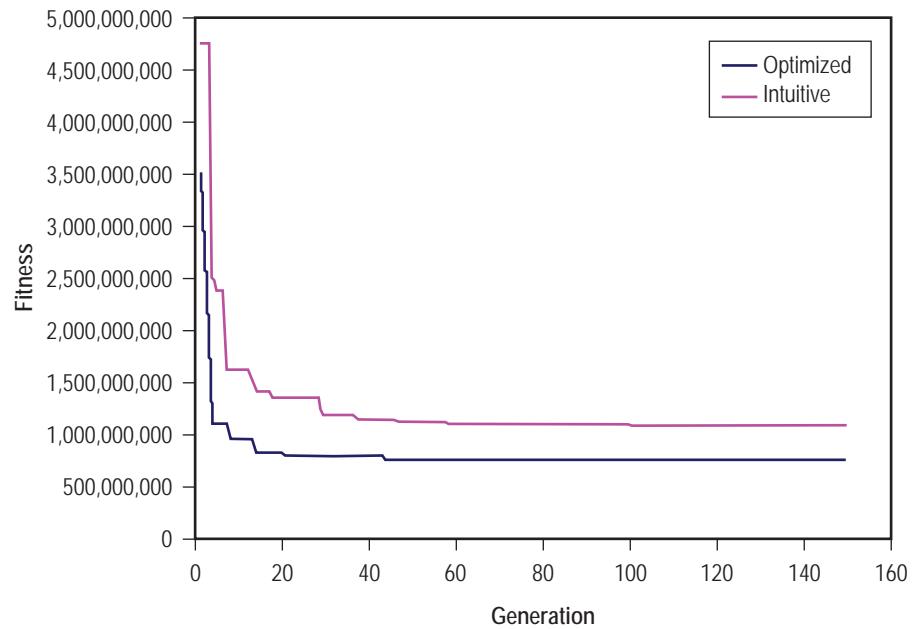


Figure 8. Optimal meta- and intuitive-GA objective function comparison.

6.1 Example Optimization Result

The results of an example optimization run are shown in figure 9. This configuration was obtained with an up-mass weighting of 6; i.e., the calculated up-mass was multiplied by 6 to allow a greater influence on the final design. Table 2 includes the constraint weightings for this optimization run. The total sum of the weightings is 1, not including the up-mass.

Habitat Cross-Section Optimal Material Configuration

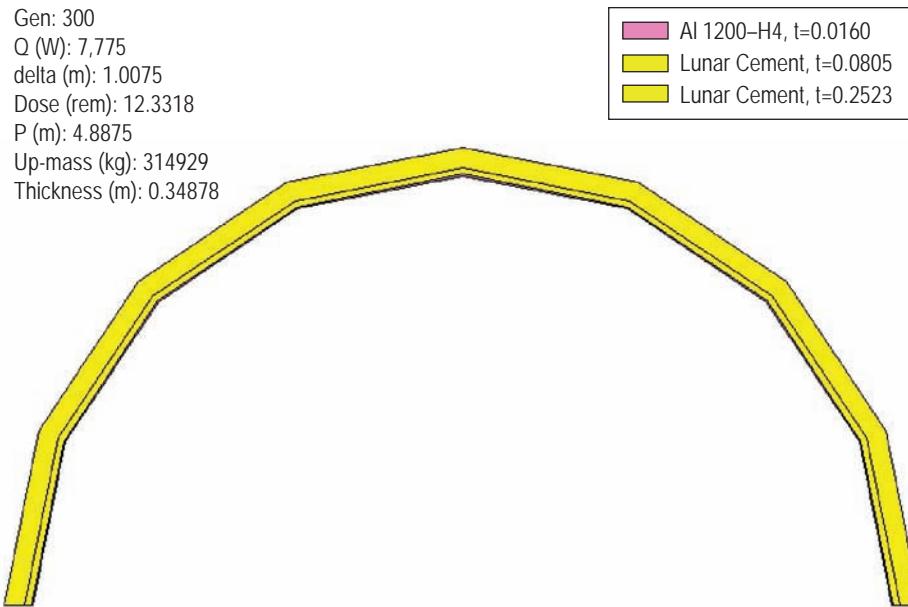


Figure 9. Example optimized habitat wall configuration.

Table 2. Weightings for example 1 optimization run.

Constraint	Weighting
Up-mass	6
Heat loss	0.3
Deflection	0.1
Penetration depth	0.3
Radiation dose	0.3

Figure 10 displays the thermal and structural ANSYS analysis plots for final example optimized habitat.

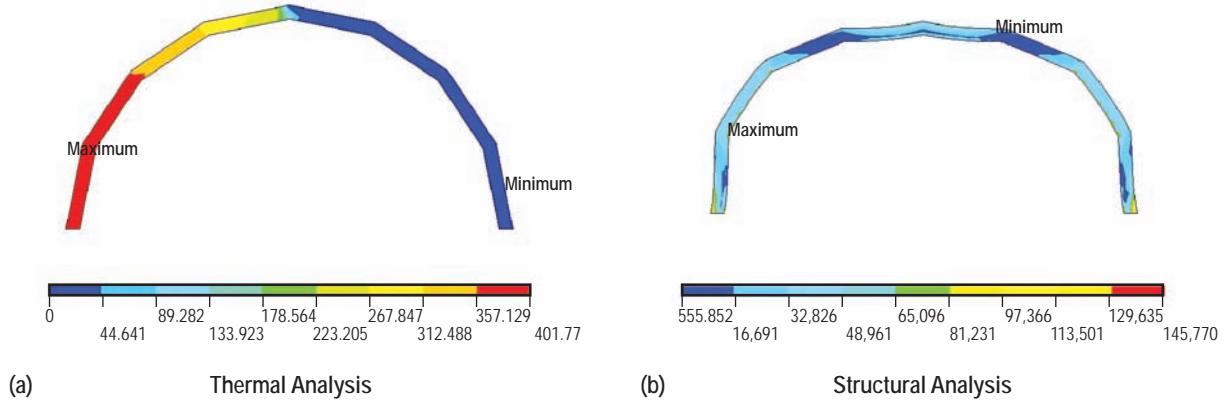


Figure 10. ANSYS plots for example 1: (a) Thermal analysis and (b) structural analysis.

This example demonstrates a design where mostly lunar regolith is chosen, which is expected since a large emphasis is placed on minimizing up-mass.

7. CONCLUSIONS

A cross-disciplinary surface habitat optimization and analysis tool has been developed that can determine a near-optimal combination of materials for the walls of a surface habitat. The tool optimizes the habitat materials for minimum up-mass including the analysis of thermal losses and gains, structural integrity, meteoroid impact, and radiation shielding. There is evident value in determining the optimal habitat wall configurations.

The GA tool, as presented in this TP, provides a preliminary optimized habitat to give a design team a starting point for more detailed engineering and analysis. The focus of the optimization can be changed by varying the weightings of each of the analysis constraints. This adds a great deal of flexibility for the user and allows the design to be focused for each application.

Also presented is a meta-GA for optimizing the GA parameters of the habitat optimization tool. This meta-GA has been proven to provide faster results and better solution sets.

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13. ABSTRACT (Maximum 200 words) Long-duration surface missions to the Moon and Mars will require bases to accommodate habitats for the astronauts. Transporting the materials and equipment required to build the necessary habitats is costly and difficult. The materials chosen for the habitat walls play a direct role in protection against each of the mentioned hazards. Choosing the best materials, their configuration, and the amount required is extremely difficult due to the immense size of the design region. Clearly, an optimization method is warranted for habitat wall design. Standard optimization techniques are not suitable for problems with such large search spaces; therefore, a habitat wall design tool utilizing genetic algorithms (GAs) has been developed. GAs use a “survival of the fittest” philosophy where the most fit individuals are more likely to survive and reproduce. This habitat design optimization tool is a multiobjective formulation of up-mass, heat loss, structural analysis, meteoroid impact protection, and radiation protection. This Technical Publication presents the research and development of this tool as well as a technique for finding the optimal GA search parameters.			
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